

HST and Optical Data on SDSSJ0804+5103 (EZ Lyn) One Year after Outburst¹

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ABSTRACT

We present an ultraviolet spectrum and light curve of the short orbital period cataclysmic variable EZ Lyn obtained with the Cosmic Origins Spectrograph on the Hubble Space Telescope 14 months after its dwarf nova outburst, along with ground-based optical photometry. The UV spectrum can be fit with a 13,100K, $\log g=8$ white dwarf using 0.5 solar composition, while fits to the individual lines are consistent with solar abundance for Si and Al, but only 0.3 solar for C. The Discrete Fourier Transforms of the UV and optical light curves at 14 months following outburst show a prominent period at 256 sec. This is the same period reported by Pavlenko in optical data obtained 7 months and one year after outburst, indicating its long term stability over several months, but this period is not evident in the pre-outburst data and is much shorter than the 12.6 min period that was seen in observations obtained during an interval from 8 months to 2.5 years after the 2006 outburst. In some respects, the long and short periods are similar to the behavior seen in GW Lib after its outburst but the detailed explanation for the appearance and disappearance of these periods and their relation to non-radial pulsation modes remain to be explored with theoretical models.

Subject headings: binaries: close — binaries: spectroscopic — novae,cataclysmic variables — stars: dwarf novae — stars:individual (SDSSJ0804+5103, EZ Lyn)

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1. Introduction

Among the new cataclysmic variables found in the Sloan Digital Sky Survey was the $g = 17.9$ mag system SDSSJ080434.20+510349.2 (Szkody et al. 2006), which has since received the name EZ Lyn. The SDSS spectrum showed Balmer emission lines with deep central absorption (indicative of high inclination) and surrounded by increasing broad absorption of the higher order Balmer lines (indicative of a large contribution of the white dwarf to the optical light). Time-resolved spectra showed an orbital period of 85 min, near the orbital period minimum (Gänsicke et al. 2009), while a 5 hour light curve showed a periodic modulation at half this period, which began with a peak-to-peak amplitude of 0.05 mag and then increased to 0.2 mag when the object suddenly underwent a brightening from 18.2 to 17.7 in blue light. No short period variations were evident in the Discrete Fourier Transform (DFT) at that time (2005 Jan). Analysis of further photometry (Zharikov et al. 2008, Kato et al. 2009) revealed a shallow eclipse of 0.05 amplitude. In 2006 March, Pavlenko et al. (2007) found the object undergoing a dwarf nova outburst at 13th mag, and another outburst at 12.5 mag was observed in 2010 September (Kato et al. 2012). Long term photometry following the 2006 outburst and throughout the quiescent interval revealed a periodicity at 12.6 min that first appeared 8 months after the 2006 outburst and lasted for about 900 days (Pavlenko 2009, Zharikov et al. 2013). This period was interpreted as possible non-radial pulsations of the white dwarf. After the 2010 outburst, this period was not evident for 11 months. However, a shorter period at 4.28 min (257s) was reported by Pavlenko et al. (2012) during 2011 April and September (7 months and 1 yr) after this outburst.

The instability strip for the accreting white dwarfs that are pulsating has been found to be wider (10,500-16,000K; Szkody et al. 2010) than the narrow strip (10,800-12,300K; Gianninas et al. 2005) for non-interacting DAV pulsators. Arras et al. (2006) suggest this is due to the metal-enriched atmospheres of the accreting white dwarfs, which enable He ionization zones as well as H. Their models show that if the He abundance is > 0.38 , there is a hot instability strip near 15,000K due to He II ionization. The cool H ionization strip merges with this one for a He abundance > 0.48 . Since it is well known that dwarf novae are heated by their outbursts and subsequently cool on timescales of several years (Gänsicke & Beuermann 1996, Sion, 1999; Piro et al. 2005; Godon et al. 2006), the dwarf novae that contain pulsating white dwarfs can provide a unique opportunity to observe a white dwarf that moves out of the strip during the outburst heating and then moves back in as it cools,

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on timescales much shorter than evolutionary ones for non-interacting pulsators. Systems such as GW Lib and V455 And show this expected type of behavior, with their quiescent pulsations disappearing for a few years after outburst and then starting to recommence at different periods (van Zyl et al. 2004, Bullock et al. 2011, Szkody et al. 2012, Silvestri et al. 2012). However, the behavior of EZ Lyn is opposite, showing possible pulsations only in the 1-2 years after outburst and not during quiescence. It raises the possibility that this system normally sits outside the strip at quiescence, then moves through it after its outburst heating.

While the optical spectra and the orbital period of EZ Lyn are very similar to those of the other accreting pulsators, EZ Lyn is unique with its low superoutburst amplitudes and its short interval between outbursts. The other known systems are similar to GW Lib, which has an outburst amplitude near 9 mag and an outburst recurrence time of 20-30 yrs, behavior that is in accordance with disk instability models for ultrashort period dwarf novae (Howell et al. 1995). In addition, EZ Lyn is also peculiar in having sporadic sharp increases in brightness of ~ 0.5 mag during quiescence, sometimes termed mini-outbursts (Szkody et al. 2006, Pavlenko 2009; Pavlenko et al. 2012). This type of sudden increase in brightness has also been observed in the system SDSSJ1238-0339 (Szkody et al. 2003, Aviles et al. 2010) which does not contain a pulsating white dwarf.

Since the temperature of the white dwarf is best determined in the ultraviolet, using the Ly α region (Gänsicke et al. 2005), and the pulsations are usually strongest in the ultraviolet as well for low ℓ modes (Robinson et al. 1995, Nitta et al. 2000, Szkody et al. 2007), we pursued Hubble Space Telescope (HST) spectra to determine the properties of the white dwarf in EZ Lyn. The 2010 outburst happened after the proposal was accepted, so the observation was obtained as late as possible in the HST cycle in order to maximize the time for the white dwarf to cool after its outburst. Ground-based observations were conducted 1.5 months after outburst and also coordinated with the HST data that were obtained 14 months after outburst.

2. Observations

The UV data were obtained during two consecutive HST orbits with the Cosmic Origins Spectrograph (COS) and the G140L grating setting of 1105 on 2011 November 3. This grating enables coverage of 1130-2000Å with a resolution of ~ 0.75 Å. The spectra were obtained in time-tag mode so that light curves could be easily constructed. The analysis used PyRAF routines from STSDAS package hstcos (version 3.14). Various extraction widths were tried to optimize the S/N, with the best value found for a width of 41 pixels. This extraction was

then applied to the summed spectrum from the two orbits.

An UV light curve was created from the time-tag data by summing the fluxes over the good S/N area of 1136-1785Å (after deletion of the strong geocoronal emission lines at 1200 and 1300Å) using 3 sec bins. This light curve was then converted to fractional amplitude by dividing by the mean and subtracting one for ease in computing a Discrete Fourier Transform (DFT).

Fast time-series optical photometric data were obtained on 2010 November 8 and a year later on 2011 November 5,7 during 2 nights that lagged the HST observations by 1.5 and 3.5 days (Table 1). The observations were accomplished using the 3.5m telescope at Apache Point Observatory (APO), with the frame transfer CCD Agile (Mukadam et al. 2011) and a BG40 filter. Measurements surrounding the outburst and the HST dates were also provided by the AAVSO network and are available from their archive². The AAVSO observations show that EZ Lyn had returned to a visual magnitude close to quiescence ($V \sim 17.8$) by 2010 October 28 (< 1.5 months after outburst). This value continued throughout the time of the HST observations.

3. UV Spectrum

The averaged and smoothed (by 3 point boxcar) COS spectrum obtained on 2011 November 3, one year after outburst, is shown in Figure 1. Except for weaker CIV1550 emission and deeper metal absorption lines, the spectrum is very similar to the dwarf nova HV Vir (Szkody et al. 2002). The broad absorption features near 1400 and 1600Å are the quasi-molecular Ly α absorption of H $_2^+$ and H $_2$ that are visible at temperatures below $\sim 18,000$ K and ~ 13000 K respectively. Besides the SiII lines at 1522,1533Å and the AlII line at 1670Å, the other strong absorption lines are CI (1355,1431,1463,1467,1561,1657Å) and CII (1323,1335Å). There is weak emission at CIII (1175Å), CIV (1550Å) and HeII(1640Å). Figure 2 shows an expanded figure with the best fit white dwarf (temperature of 13,100K, $\log g=8$, 0.5 solar abundance) obtained from a grid of models (Hubeny & Lanz 1995). This temperature places it in the middle of the instability strip for accreting pulsating white dwarfs if this temperature is the quiescent one. While some short period dwarf novae are known to take more than 3 years to cool from outburst to quiescence (Godon et al. 2006; Szkody et al. 2012), those systems have very large outburst amplitudes (8-9 mag) and long recurrence times (20-30 years). The outbursts of EZ Lyn are smaller amplitude (5 mag) and occur more frequently (4 yrs). Thus, the heating should be less and the corresponding cool-

²<http://www.aavso.org/data-access>

ing time shorter. This is corroborated by the fact that GW Lib remained 0.5 mag above its quiescent value for several years post outburst while EZ Lyn returned to optical quiescence in a few months. Thus, we expect the temperature determined from the COS data to be very close to the quiescent value.

The prominent presence of CI lines in the FUV spectrum of EZ Lyn resembles the line spectra of the white dwarfs in WZ Sge and HV Vir during quiescence, which have roughly the same surface temperature as EZ Lyn. The line feature at 1355Å, also present in HV Vir (Szkody et al. 2002), is presumed to be due to a transition of CI. In HV Vir, the increased carbon abundance required to successfully fit the strong CI 1355Å feature curiously led to line strengths for all of the other CI lines far in excess of what is observed. However, in HV Vir, the observed CI 1355 feature is considerably stronger than seen in EZ Lyn. In order to have a closer look at the chemical abundances for the individual elements C, Si and Al in the accreted atmosphere of EZ Lyn, we used the T_{eff} , and $\log g$ previously determined to generate model fits for a range of chemical abundances 0.01 , 0.1 , 0.2 , 0.3 , 0.5 , 0.7 and 1.0 times solar. The best overall fits to the individual lines reveal that the Si and Al abundances are \sim solar, while the CI abundance is \sim 0.3 times solar. Thus, the C abundance appears to be depressed relative to Si and Al. While a lower C abundance could be taken as evidence of CNO processing, our spectral range contains no N feature to determine if the abundance of N is elevated relative to C. The best overall model fit to the line spectrum occurs for a solar composition of the accreted atmosphere. This fit is shown in Figure 3.

We also tried to constrain the rotational velocity by a detailed fitting of the SiII 1526, 1533 doublet absorption lines. We tried rotational velocities of 75, 100, 150, 200, 250, 300, 350, 400 and 500 km/s with Si abundances of 0.3, 0.5, 0.7, 0.8, 0.9, 1.0, 1.5, 2.0, and 3.0 times solar, respectively. The best fitting rotational velocity is $v_{\sin i} = 225 \pm 75 \text{ km s}^{-1}$ with $Z = 1.0$ solar. The solar metal abundance that we used has an uncertainty of a factor of 2. Thus, for our range of possible $V_{\sin i}$ values between 150km/s and 300km/sec, the corresponding metal abundance Z has a possible range between $Z = 0.5$ and $Z = 2.0$ solar where the lower limit of $v_{\sin i}$ is obtained with the lower limit of 0.5 and the upper limit of $v_{\sin i}$ is obtained with the upper limit of $Z = 2.0$.

4. UV and Optical Light Curves

The light curves created from the COS data, using 3 sec binning, are shown in Figure 4. While there is obvious variability of \sim 40%, there is no apparent eclipse feature in the UV, but the phase coverage is incomplete. The eclipse is apparent in each of the 3 longer optical datasets (Figures 5-7) and the times of the bottom of the eclipse are given in Table

2. Extrapolating back from the time of the optical eclipse on 5 Nov (JD 2,445870.9094) with the period of 0.0590048d from Kato et al. (2009) shows that the eclipse would have occurred just prior to the 2nd HST orbit (the 2 orbits cover phases 0.27-0.71 and 0.08-0.71) so the eclipse is not covered. The optical data also show the double-humped variation that is typical of short period systems with low mass transfer (Patterson et al. 1998, Aviles et al. 2010, Zharikov et al. 2013). The lack of this feature in the UV data is consistent with an origin of most of the UV light from the white dwarf, which is not eclipsed, and not from the disk, which is the source of the double-hump modulation.

To search for periodic features in a quantitative way, DFTs were computed for all the data and the best fit periods were found by least-squares fits. To determine the significance of the periods, an estimate of the 3σ white noise was determined by shuffling the intensities (with the periods extracted) to create a pure white-noise light curve. The average amplitude of the DFT of this light curve then gave a 1σ measure and this was repeated 10 times to provide an empirical 3σ limit. Figures 4-7 show the original DFTs, and the resulting pre-whitened ones with the periods removed, as well as the 3σ limits. Due to the large low frequency variation present in the data obtained on 2010 November 8 (1.5 months after outburst), this trend was first removed and the DFTs computed with the original and the subtracted versions of the light curves.

The DFT of the UV light curves (Figure 4) reveals a high amplitude periodicity at 256.1 ± 0.2 sec (4.27 min) as well as a longer period at 43.2 ± 0.9 min. While the longer period could be a result of the short observation length of the HST orbits, it is more likely the first harmonic of the orbital period (84.97 min) within the error bar, as this period is often present in our longer optical datasets. The 4.27 min period is the same period reported in the Pavlenko et al.(2012) optical data obtained on 2011 April 30, September 5 and 6 (7 and 11 months past outburst). Our optical data obtained 1.5 months after outburst, close to quiescence (Figure 5), shows variability, but a period at 256 sec is not detected. Our 2011 November optical data obtained 2 and 4 days after the UV data (Figures 6 and 7) do show significant periods consistent with 256 sec (254.1 ± 1.4 s on November 5 and 255.0 ± 0.5 s on November 7). Thus, this appears to be a stable feature for over 6 months. The stability rules out a QPO feature. If this were the rotation period of the white dwarf, it would be present during all quiescent data, not merely appear after outburst. Even more puzzling is why this period is different from the 12.6 min period that lasted for ~ 900 days following the 2006 outburst.

The UV/optical ratio of the amplitudes of the 4.27 min period is $66/6=11$, a value typical for non-radial pulsators (Szkody et al. 2007). If the 13,000K white dwarf temperature is the quiescent one for EZ Lyn, it sits squarely in the middle of the instability strip, yet it is not

observed to pulsate at quiescence. A possible explanation could be that it has a relatively high He abundance so that it is too cool for the He II ionization strip which exists at 15,000K (Arras et al. 2006) and only moves through the strip after outburst heating. However, the cessation of the pulsations at quiescence and the different periods would imply that EZ Lyn is very close to the stability zone for its mass and composition and small amounts of heating are enough to displace its stability. This is consistent with the small amplitude of its outbursts (which would cause less heating). Pavlenko et al. (2012) also noted that the 12.6 min variation that was evident during the 900 days after the 2006 outburst varied in amplitude (0.01-0.03 mag) and period (732-768 sec). This wandering in frequency appears to be a common trait of accreting pulsators (Uthas et al. 2012, Szkody et al. 2012) and it is not clear what causes this effect.

GW Lib is currently the system with the most available data on the pulsating white dwarf following its outburst (Szkody et al. 2012, Chote & Sullivan 2013). Even though there are obvious differences in the outbursts and in the quiescent pulsation spectrum of the two systems, their behavior after outburst contains some interesting commonalities. Both exhibit a long period and a short period that appears to be triggered by mass accretion. In GW Lib, this period is near 19 min (Copperwheat et al. 2009, Bullock et al. 2011, Vican et al. 2011) vs the 12.6 min in EZ Lyn. In both of these systems, the long period was observed to appear in the year following the outburst, when the system had returned to close to its quiescent level. In GW Lib, this period lasted for 4 months, while in EZ Lyn for 2.5 years. The short periods that appear in both UV and optical data when the long period is not present are 290 sec in GW Lib (Szkody et al. 2012) and 256 sec in EZ Lyn. This short period was evident from 3-4.25 years past outburst in GW Lib, and then was replaced by the return of the 19 min period during the 5th year after outburst (Chote & Sullivan 2013). The short period in EZ Lyn appeared 7 months after the latest outburst and lasted for at least 6 months. While these periods are generally incoherent over several nights, the study of the 19 minute period present in 2012 in GW Lib revealed coherence over 2 nights, with combinations of frequencies that were consistent with non-radial g-modes (Chote & Sullivan 2013).

The thermal timescale at the base of the convection zone dictates which pulsation modes are excited, so longer periods are expected as the star cools and the base of the convection zone sinks deeper in the white dwarf (Brickhill 1992, Goldreich & Wu 1999, Wu 2001, Montgomery 2005). If both the long and short periods are related to non-radial pulsation, then the only way to observe short period modes after the excitation of longer periods, is for the white dwarf to undergo accretion-related heating. The change from short to long periods as the white dwarf cools is consistent with being due to the excitation of a different mode at lower surface temperatures. However, conclusions about what the mode frequencies mean

about the interior of the star and the development of a consistent picture of the changing excitation requires further theoretical work.

5. Conclusions

Our COS spectrum of EZ Lyn obtained in 2011 November, 14 months after its dwarf nova outburst, shows prominent absorption lines from a white dwarf that is consistent with a temperature of 13,100K, and $\log g=8$. The lines of Si and Al indicate a metal composition near solar, while the C abundance is only 0.3 solar. The UV and optical light curves reveal a significant periodicity at 256 sec, with an expected higher amplitude in the UV than the optical. This period is identical to that evident in the optical in April and September 2011 (Pavlenko et al. 2012). While this appears to be a non-radial pulsation that is triggered by the outburst, the difference in behavior from data obtained after a previous outburst in 2006 (Pavlenko 2009), which showed a longer period at 12.6 min remains to be explained.

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Table 1. Summary of Observations

UT Date	Obs	Instr	Filter	UTC Time	Exp (s)
2010 Nov 8	APO	Agile	BG40	07:11:59-08:36:54	5
2011 Nov 3	HST	COS	G140L	21:22:58-22:00:34	Time-tag
2011 Nov 3	HST	COS	G140L	22:32:27-23:25:06	Time-tag
2011 Nov 5	APO	Agile	BG40	09:39:58-12:02:28	30
2011 Nov 7	APO	Agile	BG40	07:59:40-12:16:05	30-60

Table 2. Eclipse Times

UT Date	UTC Time
2010 Nov 8	08:30:49
2011 Nov 5	09:49:28; 11:14:08
2011 Nov 7	09:57:51; 11:22:51

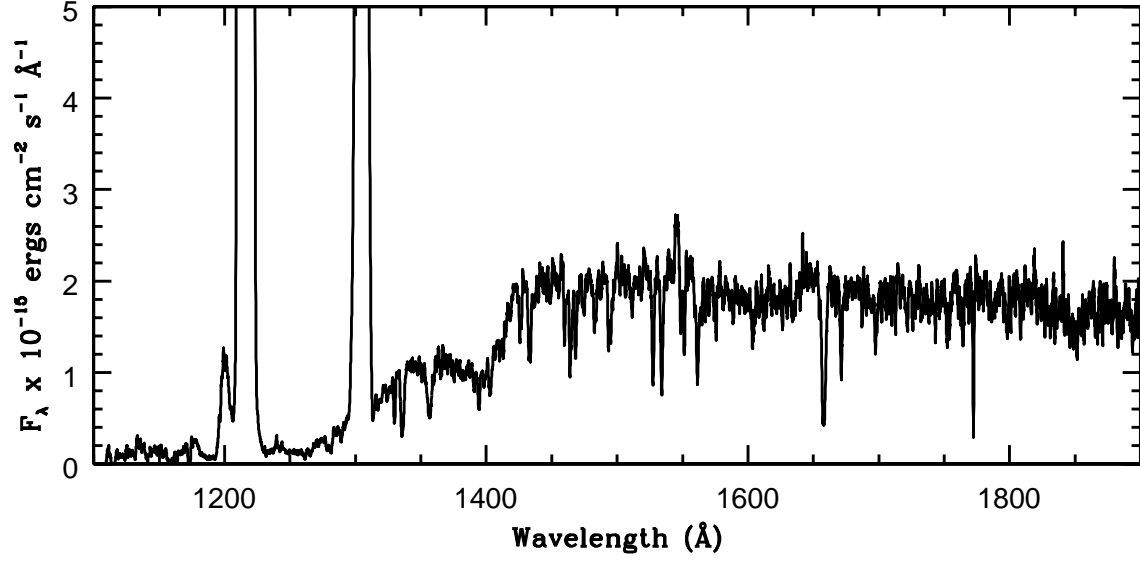


Fig. 1.— COS G140L spectrum 2011 Nov 3 (14 months after outburst) smoothed with a 3pt running boxcar. Strong emission lines are airglow from Ly α and OIII.

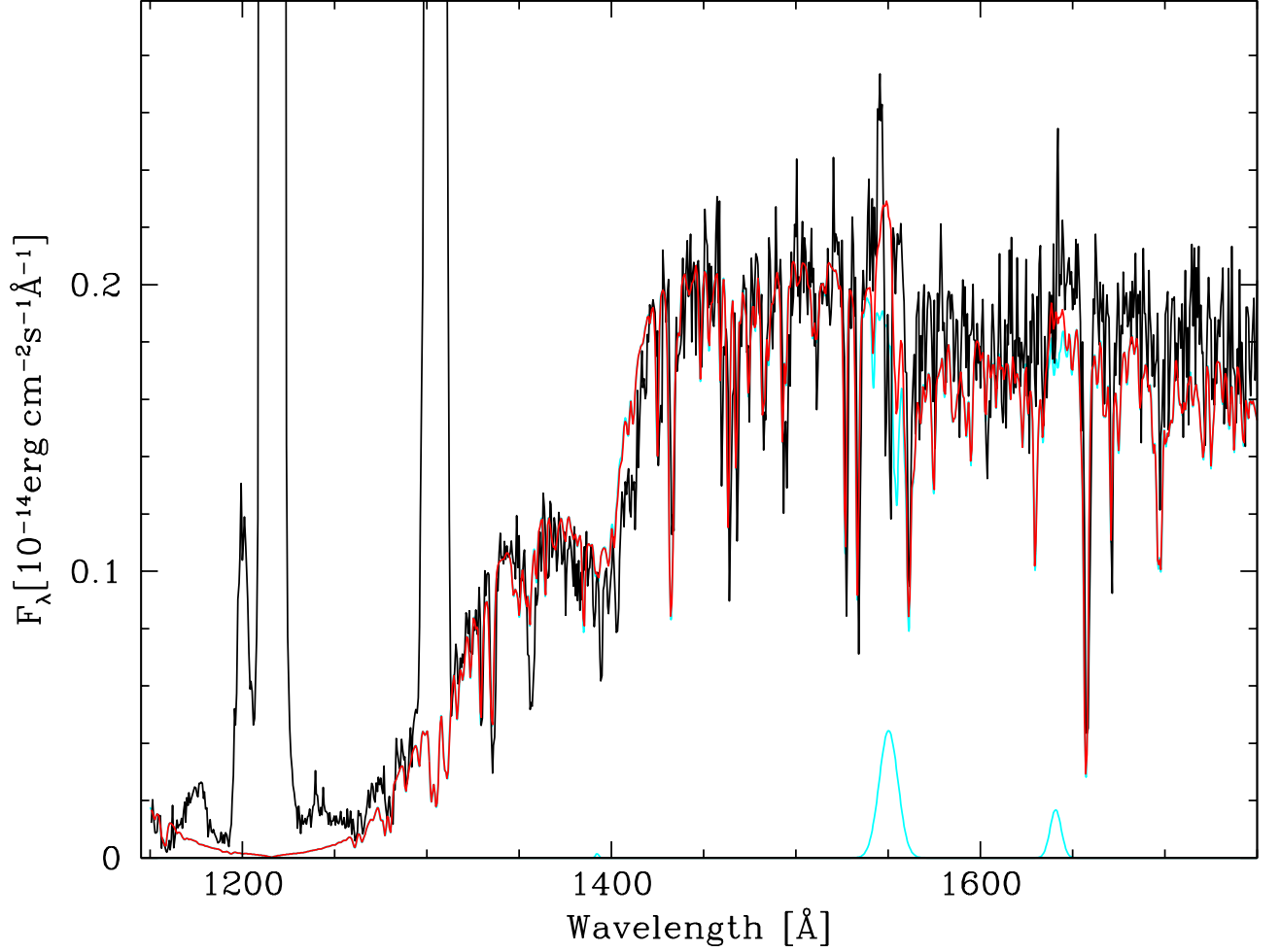


Fig. 2.— COS spectrum (black) fit with a 13,100K, $\log g=8.0$ white dwarf with 0.5 solar composition (red). CIV and HeII emission lines are represented by Gaussians (blue).

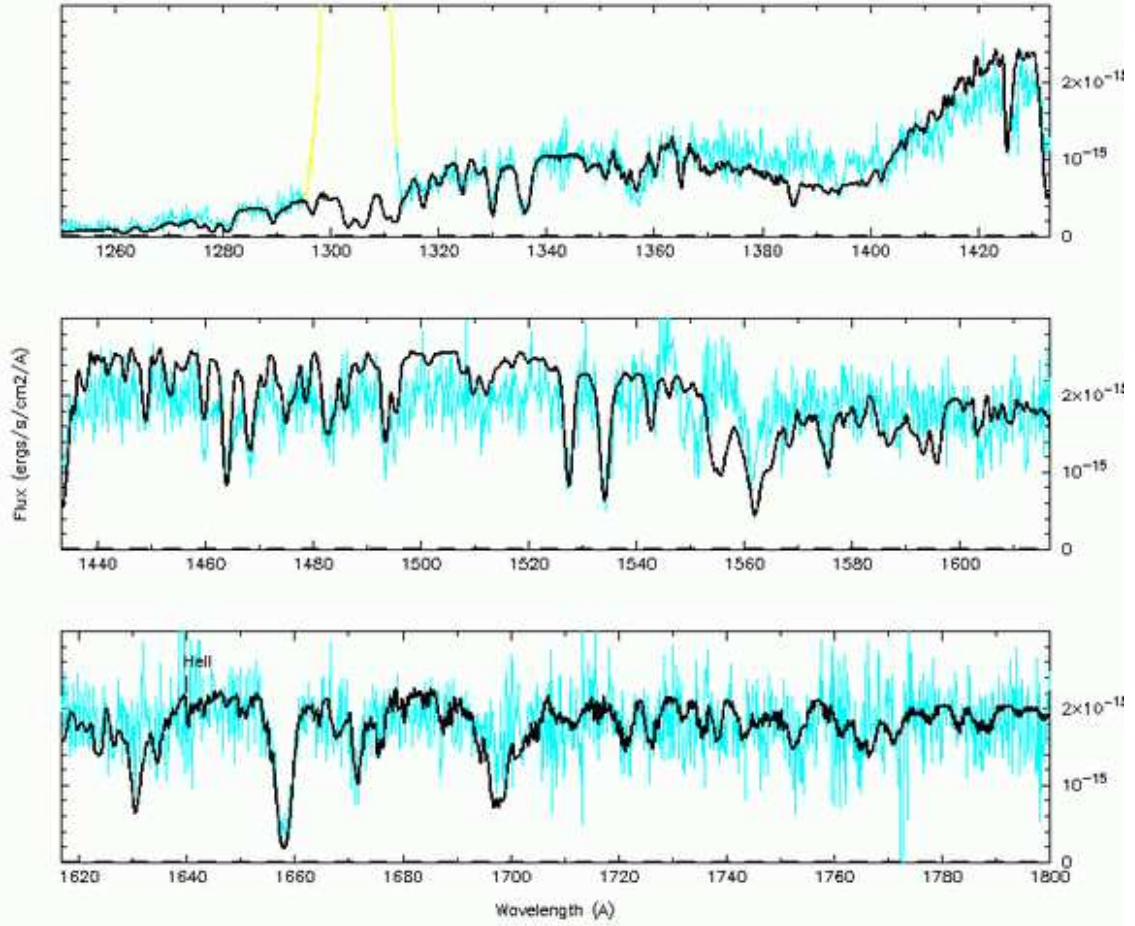


Fig. 3.— COS spectrum fit with a 13,000K, $\log g=8$ solar composition white dwarf. Fits to individual lines yield solar abundances for Si and Al and 0.3 solar for C.

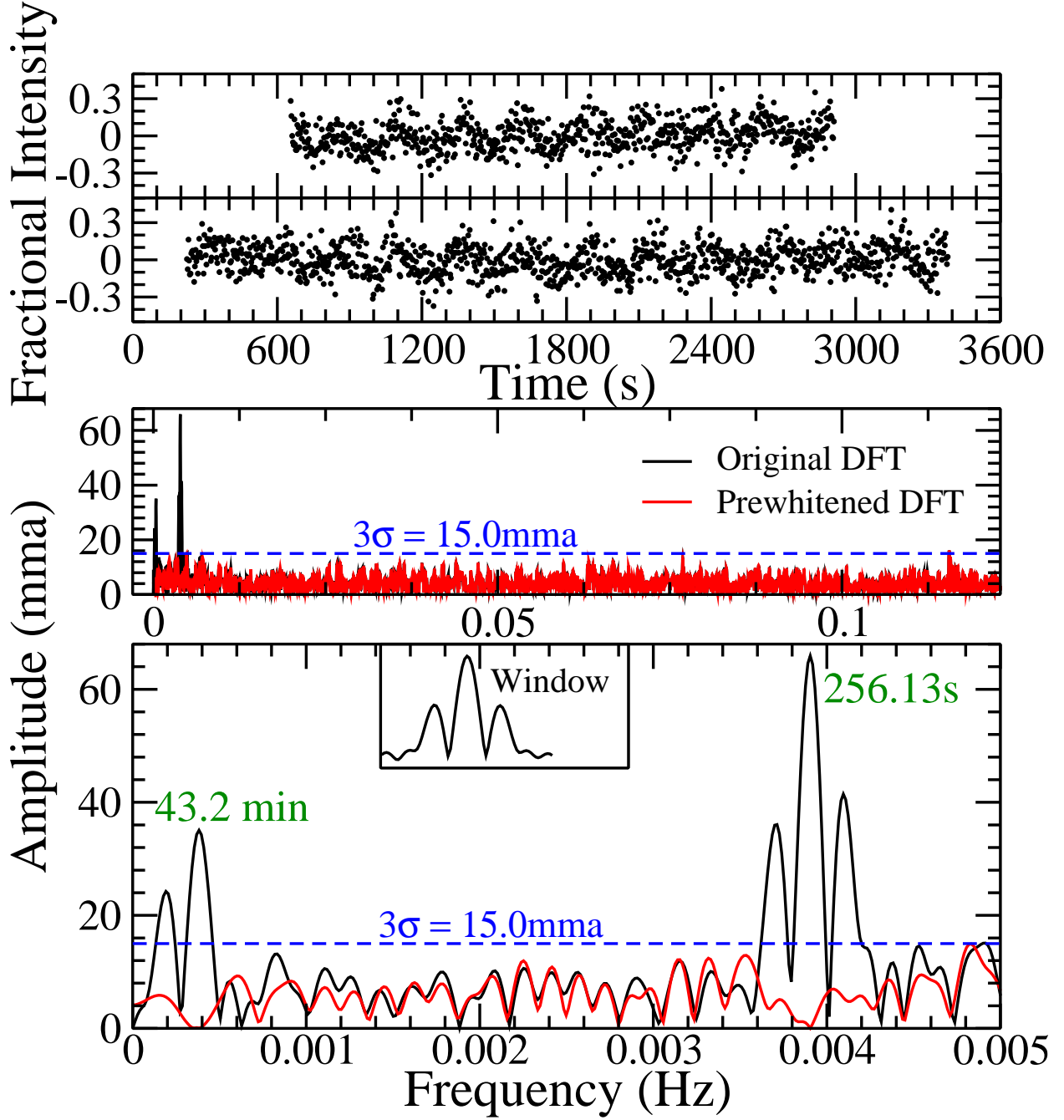


Fig. 4.— COS intensity light curve 14 months after outburst with 3s bins (top), DFT (middle) and an expansion of the low frequencies (bottom). Dashed line shows the 3σ noise limit found from the shuffling technique. Inset on bottom shows the window function for the data. The 256 sec period is well-detected.

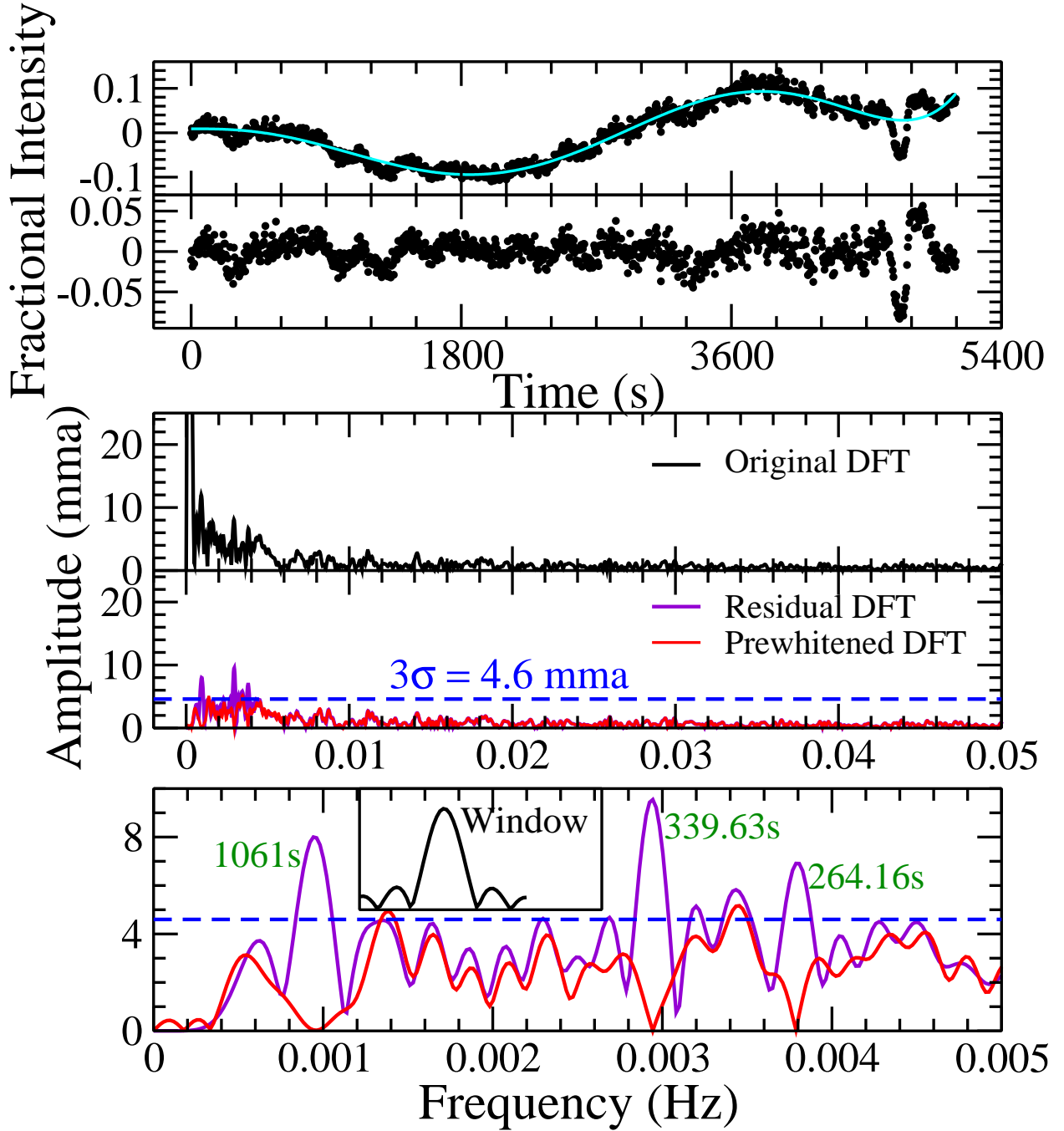


Fig. 5.— APO 2010 November 8 data 1.5 months after outburst at magnitude 17.7 ± 0.2 . Top panel shows original intensity light curve with 5s exposures; underneath is this light curve with a low order polynomial fit subtracted to remove the low frequency trend. Middle panels 3 and 4 show DFTs of the above light curves while the bottom panel shows an expansion of the low frequencies in panel 4 and an inset with the window function. Dashed lines show the 3σ noise limit found from the shuffling technique. The pronounced dip near the end of the light curve is the partial eclipse, with time listed in Table 2. The 256 sec period is not evident but is likely masked by the other variability due to the outburst.

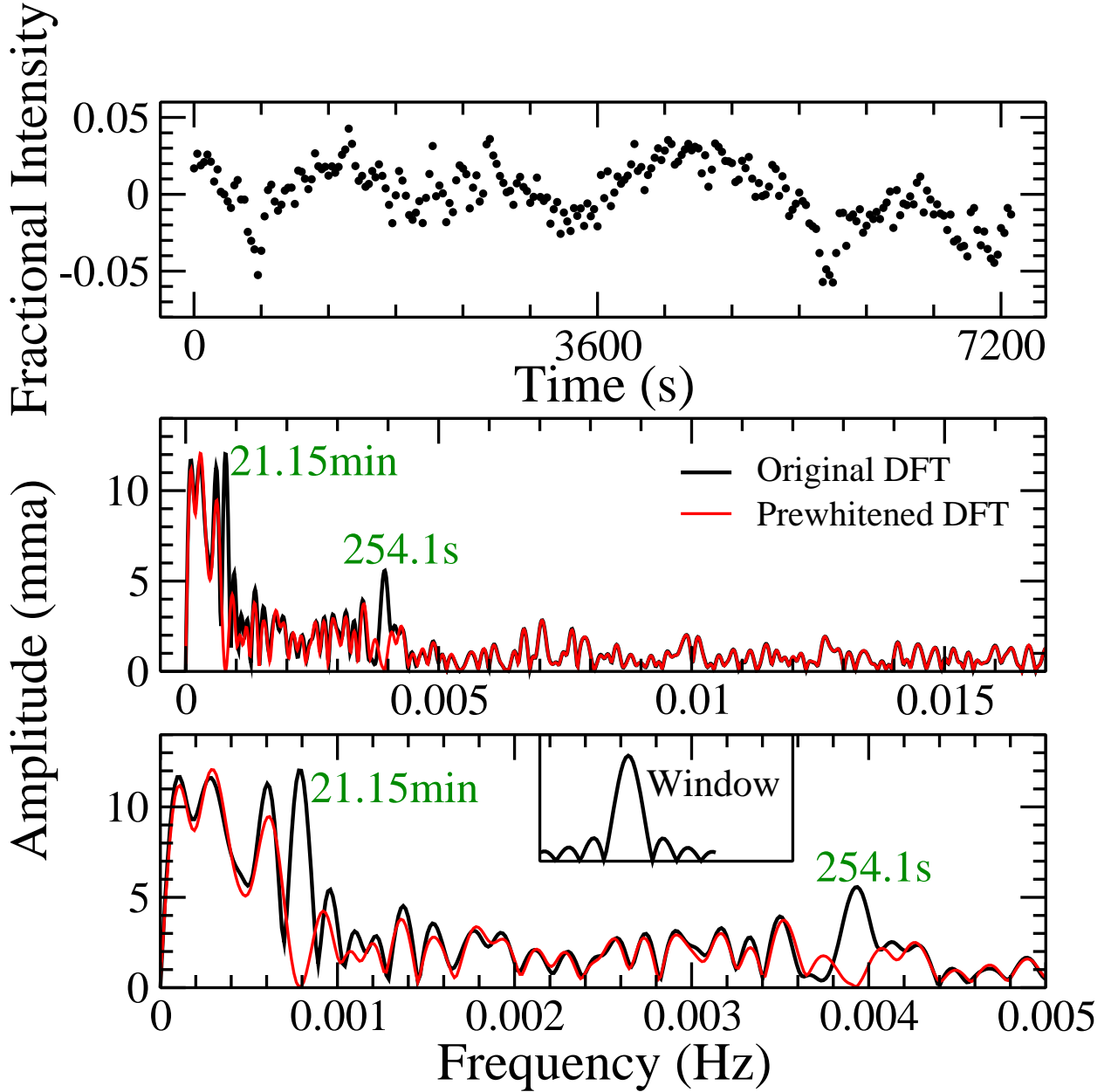


Fig. 6.— Similar to Figure 4 showing APO data from 2011 November 5 (14 months after outburst) at magnitude 17.8 ± 0.1 with 30s exposures. Two partial eclipses are evident in the light curve (Table 2). A signal consistent with the 256 sec period evident in the COS data is detected. Due to the short length of the dataset, the shuffling technique could not produce a good value of 3σ over the entire frequency range but an estimate for frequencies > 0.005 Hz is 2.9 mma.

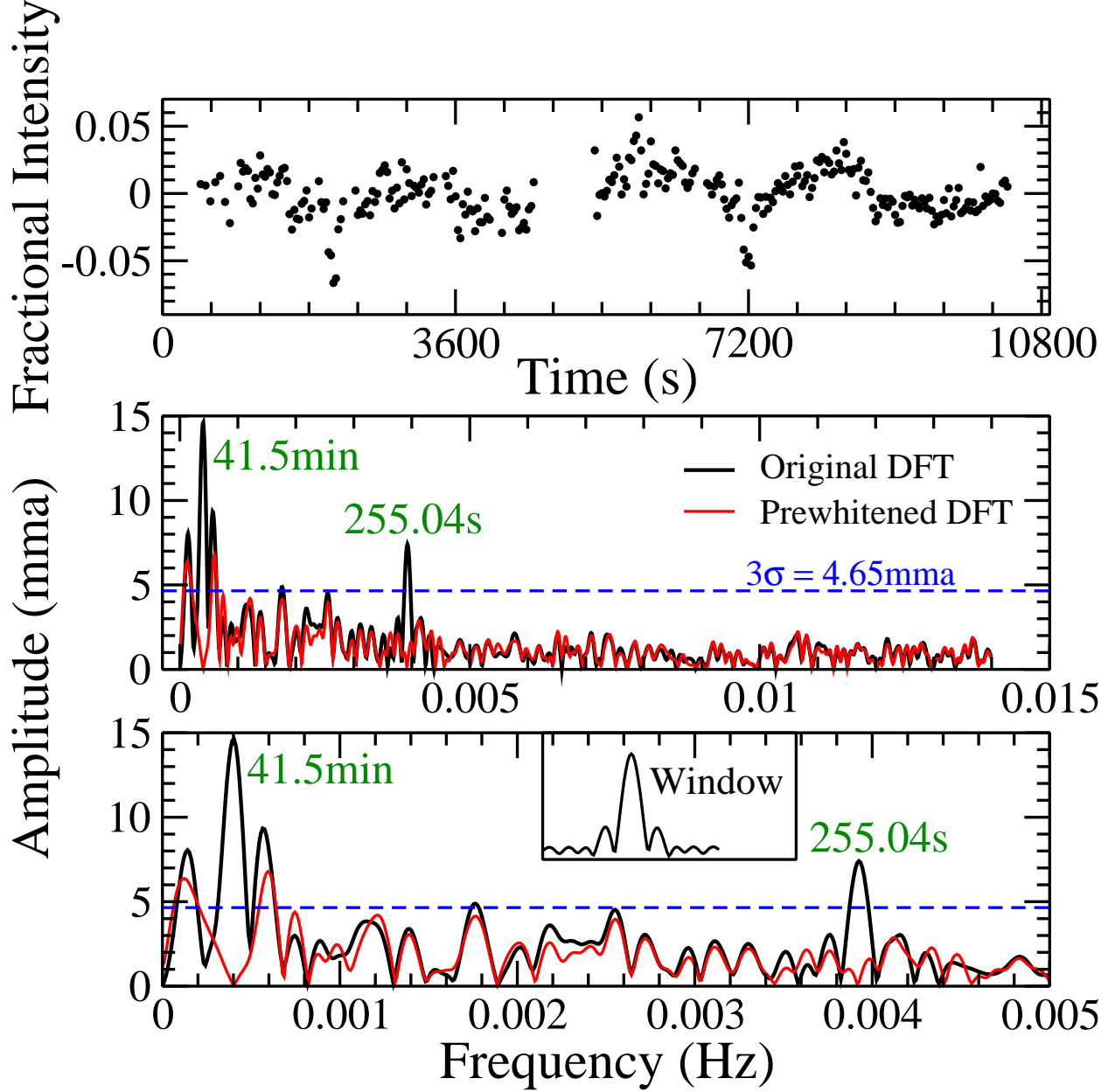


Fig. 7.— Similar to Figure 4 with data from APO with 30-60s exposures on 2011 November 7. Mean magnitude is 17.5 ± 0.1 and 2 partial eclipses are present (Table 2). The 256 sec period is even more robustly detected in this longer dataset.